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PART 2: LIGHTING TECHNOLOGIES IN SOME APPLICATIONS

PHOTOBIOLOGICAL EFFICIENCY OF RADIATION OF LED RADIATORS FOR CENOSES OF DIFFERENT AGE PLANTS IN RELATION TO CONDITIONS OF CLOSED ECOSYSTEMS

Alexander A. Tikhomirov[1, 2], Vladimir V. Velichko[1, 2], and Sofya A. Ushakova[1]

[1] *Institute of Biophysics of the Federal Research Centre, Krasnoyarsk Science Centre of the Siberian Branch of the Russian Academy of Sciences, Krasnoyarsk*
[2] *M.F. Reshetnev Siberian State University of Science and Technology, Krasnoyarsk*
E-mail: alex-tikhomirov@yandex.ru

ABSTRACT

The paper presents experimental data on the photo-biological efficiency of the emission of white light LED irradiators and phyto-spectrum with an intensity of 460 μmol/(m^2·s) and 800 μmol/(m^2·s) at the intermediate (18 days) and final (27 days) stages of the growing season of growing Chinese cabbage (Brassica rapa), chard (Beta vulgaris), and radish (Raphanus sativus) in relation to the conditions of closed ecosystems (CES). The presence of different specifics of the reaction of plants to the spectral composition of radiation, both at the intermediate and final stages of vegetation, has been established. It has been suggested that in some plant species (Chinese cabbage) it may be physiologically justified at the intermediate stage of vegetation to change the spectral regime of irradiation from the phytospectrum to white light in order to achieve higher productivity values. Using the example of chard, it has been established that the phyto-spectrum can be more effective than white light when growing leaf biomass, regardless of the growing season. Using the example of radishes, it was shown that the phytospectrum stimulates the accumulation of high values of above-ground biomass in comparison with white light, however, for the accumulation of root biomass in relation to the conditions of the CES, it is more expedient to use white light, since with a biomass of root crops comparable to the phytospectrum, plants with an increased coefficient of economic efficiency are formed in white light, which reduces the share of waste in the CES (inedible leafy biomass). On the basis of the data obtained, possible tasks of scientific research on evaluating the spectral efficiency of radiation at certain stages of plant vegetation, as well as the prospects for creating LED irradiators with a physiologically based program for regulating the spectral composition and radiation intensity, are discussed.

Keywords: photo-biological efficiency of radiation, LEDs, phytocenosis, vegetation periods, regulation of the spectrum and irradiance of PAR, CES

1. INTRODUCTION

For conditions of closed ecosystems (CES), selection of an efficient combination of irradiance and spectrum of photosynthetically active radiation (PAR) plays the most important role in formation of plant performance, and light emitting diode light sources may be very prospecting [1]. Using light sources of the previous generations, it was demonstrated that spectral efficiency of radiation may depend significantly on the irradiance level of PAR luminous flux [2]. This pattern was qualitatively confirmed and further developed when using contemporary LED equipment [3]. Conditions of

PAR irradiance selection for the phototrophic part of space ecosystems may be based on one of the two criteria. The first of them is related to significant limitation of power consumption when, for instance, plants are cultivated in mini greenhouses as a vitamin additive for nutrition of a space ship or an orbital station crew [4]. In this case, it may be reasonable to use irradiance levels corresponding to the linear region of the light distribution curve of phytocenosis photosynthesis, which is closely related to its energy efficiency of photosynthesis [5]. According to the second criterion, necessity to provide a human with maximum possible yield of plant products from a unit area becomes the most important factor. For this purpose, rather high PAR irradiance levels are required. Simultaneously, exceptionally important problems such as provision of human with oxygen, disposal of excessive carbon dioxide, water supply by means of transpiration moisture as well as a number of associated problems are being solved. Selection of the second criterion is common for plant cultivation in CES conditions planned to be allocated on celestial bodies (planets, their natural satellites, asteroids) [1].

Usually all photo-biological studies for evaluation of the role of PAR intensity and radiation spectrum for plants are conducted with constant light chromaticity over the entire vegetation period. The problem of reasonability to change the PAR radiation spectrum at different plant vegetation stages in order to increase their ultimate productivity remains virtually unstudied for space applications (and actually for Earth-based applications as well). To evaluate the reasonability of such studies, it is necessary to conduct photo-biological experiments allowing to evaluating experimentally legitimacy of such problem statement. The contemporary LED equipment provides rather broad prospects for solving this problem since it allows us to vary the level of irradiance and radiation chromaticity across the entire required range of optical radiation.

In view of this, this paper considers the effect of radiation chromaticity and irradiance levels of LED radiators on photosynthetic performance of plants that may be cultivated in CES at different stages of their vegetation.

2. METHODS

To study the effect of PAR irradiance and chromaticity on plant performance, the plants of chard (*Beta vulgaris*, Charlie cultivar), Chinese cabbage (*Brassica rapa*, Krasa vostoka cultivar), and radish (*Raphanus sativus*, Mokhovskiy cultivar) were selected. All these plant cultivars are classified as early vegetable crops resistant to stooling under round-the-clock irradiation, which have been actively used for plant cultivation in CES conditions [6]. The plants were cultivated in temperature-controlled vegetation chambers using a fresh soil-like substrate (SLS) adapted to conditions of closed ecosystems using the previously described methods [6]. The studied plants were cultivated in stainless steel vegetation vessels. Before seeding the plants, 2500 g of SLS on a wet weight basis or (910–928) g of the same on a dry weight basis were placed into a vessel. Watering was performed by saturating SLS once a day after which the irrigating solutions with extractive elements flowed by gravity from the substrate to the watering tanks.

The seeds of cabbage, chard and radish were seeded in vegetation boxes on the depth of 1 cm from the upper level of the SLS expanded clay in an amount of 188 pieces per m^2. Spacing between the plants was 8 cm in a row and 7 cm between rows. Air temperature was maintained at the level of (24±1) °C with relative humidity of (60–70) % and atmospheric concentration of CO$_2$.

Plant performance was analysed twice: at the plant age of 18 days and in the end of vegetation at the age of 27 days. To compare the performance indicators of the studied lighting variants, the relative plant growth rate was determined using the formula:

$$(M_2 - M_1)/M_1T,$$

where M_1 is the average dry biomass of 18-day plants, g; M_2 is the average dry biomass of 27-day plants, g; T is the cultivation duration over the last 9 days, days.

When calculating the performance characteristics, deviations from the mean-square values did not exceed 10 %.

Round-the-clock lighting was used with different PAR irradiance on the level of upper leaves of the plants: irradiance of 460 μmol/(m^2·s) corresponding to the linear region of the phytocenosis photosynthesis light distribution curve and increased irradiance of 800 μmol/(m^2·s) which may cause significant increase of biomass yield from a unit area which in turn results in reduction of CES weight or increase of the number of crew mem-

Fig. 1. Appearance of the radiators used for the experiments: ACC-300 (top photo) and ACC-300 Agro (refer to the description in the text)

bers without increasing its size [7]. Deviations from the average level of irradiance of the illuminated areas (0.28–0.3) m^2 of each crop did not exceed 10 %. A Li-250A instrument with a Q-35016 quantum sensor (Li-COR, USA) was used to measure the irradiation levels in the PAR region, and an AvaSpec-ULS2048-USB2 spectrometer (Avantes, the Netherlands) was used for monitoring of spectral energy distribution of the used light sources.

During the studies, two types of light emitting diode radiators were used with their radiation chromaticity appearing to be prospective for use in CES conditions as well as for a broad range of Earth-based applications, according to our findings [1]. PAR radiation spectrum of the first type of radiators is perceived by human eye as white light (hereinafter referred to as the white light) and the radiation spectrum of the second radiator type simulates the average absorption spectrum of a green leaf (hereinafter referred to as the phytospectrum). ACC-300 LED radiators (ACC, Russia) were selected as the white light sources and ACC-300 Agro LED radiators (ACC, Russia) were selected as the sources of phytospectrum radiators. The appearance of the abovementioned light sources is presented in Fig. 1. The radiation spectra of the selected light sources are presented in Fig. 2.

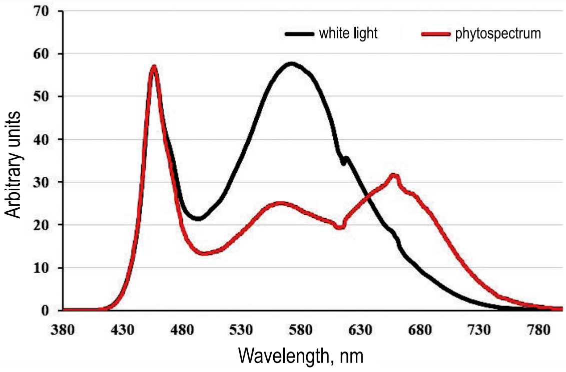

Fig. 2. Radiation spectra of the ACC-300 and ACC-300 Agro LED radiators (refer to the description in the text)

3. RESULTS

Fig. 3 presents the experimental data on the effect of irradiance level and light chromaticity on cabbage biomass at the intermediate and final vegetation stages. At the intermediate vegetation stage (18 days), statistically significant higher radiation efficiency under the phytospectrum was noted only for the increased irradiance of 800 μmol/(m$^2\cdot$s), as compared to white light. At the final vegetation stage, the influence of the studied spectra on cabbage biomass did not provided statistically significant differences for both irradiance levels used. Interestingly, however, that at the second vegetation stage (19–27) days the rates of cabbage biomass accumulation were higher under the white light with PAR intensity of 460 μmol/(m$^2\cdot$s).

With PAR irradiance of 800 μmol/(m$^2\cdot$s), lag in biomass observed under the white light at the age of 18 days was mitigated at the final stage of the vegetation and the differences in final crops appeared to be statistically insignificant. While the Chinese cabbage biomass growth rate under the phytospectrum was twice as high as the biomass growth rate under the white light at the first stage of vegetation, at the subsequent stage, the growth rate was 0.33 g per plant per day for both spectral variants. This being said, the relative biomass growth rate under the white light (ref. to the Table) was actually two times higher than that under the phytospectrum (0.30 g

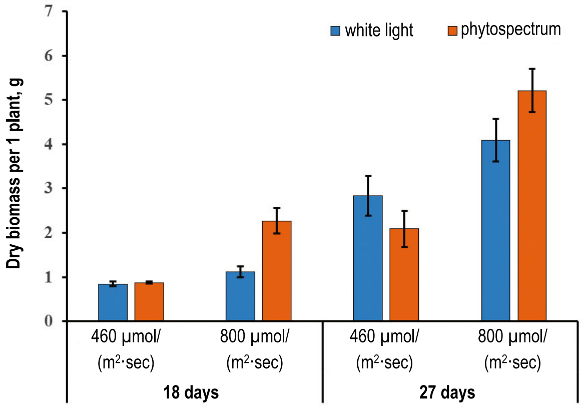

Fig. 3. Aboveground biomass of cabbage plants grown with different lighting modes depending on the plant age

Table. Relative Growth Rate (G/Day, g) per Dry Biomass of One Plant for Cabbage, Chard and Radish Cenoses over a Period of (18–27) Days Grown at Irradiance of 460 μmol/($m^2\cdot$ s) and 800 μmol/($m^2\cdot$ s) under ACC300 LED Irradiators (White Light) and ACC Agro 300 (Phytospectrum)

Type of plant		Spectrum of irradiator			
		White light, μmol/($m^2\cdot$s)		Phytospectrum, μmol/($m^2\cdot$s)	
		460	800	460	800
Cabbage		0.26±0.03	0.30±0.02	0.15±0.02	0.15±0.02
Chard		0.64±0.05	0.42±0.04	0.86±0.09	0.36±0.03
Radish	Total biomass	0.12±0.02	0.15±0.02	0.28±0.03	0.37±0.04
	Root crops	0.41±0.04	0.17±0.02	0.57±0.05	0.32±0.03

growth per 1 g of dry mass per day vs 0.15 g growth per 1 g of dry mass per day). It is also seen from the Table that white light efficiency in accumulation of the Chinese cabbage biomass at the second vegetation stage was significantly higher than when using the phytospectrum with both levels of PAR irradiance used. It may be assumed that switching from the phytospectrum to white light for cabbage plants at the second vegetation stage with all irradiance levels may be useful for increasing of plant crop.

Fig. 4 presents the data on accumulation of aboveground biomass in the chard plants depending on the used levels of irradiance and chromaticity of the lighting modes. Analysis of the data demonstrated that plants grown under the phytospectrum accumulated larger aboveground biomass as compared to the plants accumulated under the white light irrespective of the studied levels of irradiance and plant age. For instance, if the values of the aboveground biomass had significant differences between the lighting modes at the age of 18 days, by the end of the vegetation, they had been statistically significant for all the compared lighting variants. As seen from the data in the Table, the highest relative growth of the aboveground biomass during the second half of the vegetation period was observed at 460 μmol/($m^2\cdot$s) under the phytospectrum and white light. It may be assumed that switching the radiation spectrum in the studied lighting variants at the intermediate vegetation stage may be unnecessary for chard plants.

Fig. 5 presents the data on formation of radish biomass with the studied levels of irradiance and PAR chromaticities. With respect to the CES conditions, it is reasonable to consider not only accumulation of the total biomass of this culture (root crop and aboveground biomass) but also accumulation of the root crops since it is important to know which portion of the biomass is waste which, in this case, is non-edible aboveground biomass. Therefore, apart from the total radish biomass data, Fig. 5 shows the biomass percentage of the root crops, i.e. the value of the economic effectiveness ratio (K_{ef}). The analysis of the data in this figure showed that the phytospectrum stimulated larger accumulation of the total biomass than white light with both irradiance levels used. The relative growth rate data (refer to the Table) shows that the relative total biomass growth is also higher for the phytospectrum than for the respective variants under the white light. At the same time, the value of K_{ef} was higher under the white light than under the phytospectrum. Due to that, the absolute values of the edible biomass in the white light variants were confidently not lower than those under the phytospectrum despite the fact that in the latter case, the aboveground biomass was significantly larger. The relative root crop biomass growth rate over the period of (19–27) days (refer to the Table) was higher for the phytospectrum variant, however, that did not lead to statistically significant differences in the final crops for

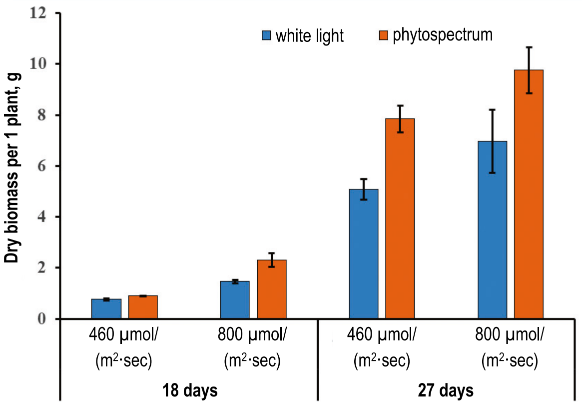

Fig. 4. Aboveground biomass of chard plants grown with different lighting modes depending on the plant age

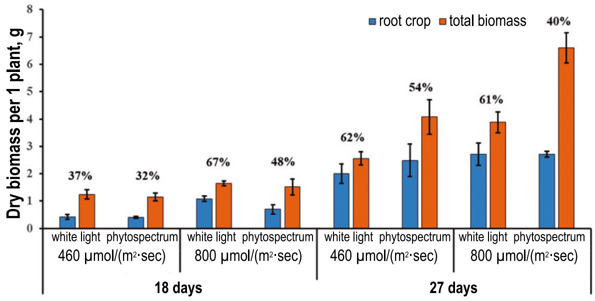

Fig. 5. The biomass of the radish plants (the root and the aboveground biomass) grown in different lighting modes at different ages (the percentages reflect the values of K_{ef} for each presented lighting variant, explanation is in the text)

both spectral variants. Based on this data, it may be assumed that there are no reasons for changing the spectral mode of radish cultivation in the second half of the vegetation period at 460 μmol/(m^2·s). With irradiance of 800 μmol/(m^2·s), the value of K_{ef} under the white light was constantly higher both after 18 and 27 days of vegetation, which, as noted above, determined approximately equal values of the edible biomass crop. This was promoted by higher relative biomass growth rate of the root crops at the final stage of the vegetation when using the phytospectrum (Table), which caused mitigation of the lag in this indicator obtained in the first half of the vegetation period for this spectral variant, Fig. 5. Due to the fact that the portion of the non-edible aboveground biomass was much higher with increased irradiance under the phytospectrum than under the white light, it may be assumed that using white light with increased irradiance is more preferable for CES than using the phytospectrum since this leads to reduction of the waste proportion and increases closure of the mass-exchange processes.

4. DISCUSSION

The studies demonstrate not only that the plants of different species have different specifics of response to PAR chromaticity, which has already been confirmed by different researchers [8, 9], but also that in some cases this specifics may be manifested at different vegetation stages, which may depend on the plant age. In particular, this assumption is based on the data of the photo-biological experiments with the Chinese cabbage. For instance, in cabbage plants, high biomass accumulation growth rate was observed over the entire period of vegetation under the white light with irradiance level of 460 μmol m^2·s whilst at the level of 800 μmol/(m^2·s), this photo-biological efficiency of the white light manifested itself only at the final vegetation stage, which eventually led to actual equalisation of the final performance values in the considered lighting modes. Therefore, changing of radiation chromaticity in the course of plant vegetation (as exemplified by the Chinese cabbage) may be useful for increasing the final plant performance and may depend not only on the plant species but also on the selected level of PAR irradiance. Of course, as it is demonstrated for chard in this paper, changing of the radiation spectra during vegetation may be unnecessary. At the same time, depending on the goals and conditions of plant cultivation, changing of the spectral mode of radiation may be reasonable in the course of vegetation. This has been demonstrated in the course of the experiments with radish presented in this article when not the total biomass but the edible biomass of plants is important in conditions of closed ecosystems.

Therefore, the obtained experimental data allows us to assume that the need of plants for the radiation chromaticity may change in the course of vegetation to increase their final crop and it is important to account for it for photo-culture conditions both for Earth-based and space applications. In other words, it is referred to dynamic control of LED lighting chromaticity which may be implemented by creating physiologically substantiated software control means for LED equipment allowing to changing spectral lighting environment during the required vegetation periods, which may be necessary for optimisation of the growth and development over the entire life cycle of plants. It is likely that the radiation spectrum optimal for the plant growth and development changes with its age, therefore, the plants need to balance their habitus including leaf areas, stem growth as well as processes related to reproductive growth and development [10]. The process of plant blossoming plays a special role since this process is one of the most important factors of edible biomass formation, therefore, it essentially determines formation of crops. This process is aligned with a specific stage of plant vegetation and light chromaticity plays the key role in this process. In particular, it is found that a balanced combination of red and far-red radiation promotes plant blossoming [11]. The same researchers have demonstrated that the luminous flux of LED sources enriched by red radiation efficiently delays blossoming of plants at a specific vegetation stage [12]. Therefore the works aiming at understanding of physiological and photo-biological mechanisms forming the basis of this and other processes inherent at specific stages of the vegetation period shall be the essential aspect of such studies. This requires the use of plant species with explicit phases of growth and development as objects of such studies when evaluation of changes in spectral and energy characteristics of irradiation modes at different stages of ontogenesis may be prospective. Plants used for such studies often form multi-layer phytocenoses. It is not unlikely that not only the conventional overhead lighting but also the internal phytocenoses lighting shall be used at specific vegetation stages in order to prevent reduction of photosynthesis and preliminary aging of the middle- and upper-layer leaves and thus to increase performance and total crop [13].

It is clear that the considered prospects of irradiation mode changing at specific vegetation stages may turn out to be not always reasonable, which may be caused by adaptation and other physiological responses. Therefore, the ultimate answers to these questions may be obtained only by means of direct experiments with changes of spectral irradiation modes at different stages of vegetation.

Deep understanding of the energy balance required by plants for regulation of growth and development over their entire life cycle is very important for development of light sources and their subsequent use in photo-culture conditions for both space and Earth-based applications. Successful implementation of this approach using light sources of previous generations was very difficult and hardly producible. Hopeful prospects appear if light emitting diode lamps are used for a photo-culture. According to the information available, such attempts have been already made. In particular, a number of researchers have created installations with adjustable radiation spectra for different stages of vegetation by using different combinations of light emitting diodes of different chromaticity [14]. Adjustable-spectrum light emitting diodes have been developed [15] to be applied for general lighting and a number of medical applications, although further improvement of their design does not rule out their application for photo-culture conditions. In general, the problem of development of relatively cheap and simply controlled LED radiators with radiation spectrum and intensity easily adjustable in accordance with the set programme appears to be rather prospecting and physiologically reasonable. The results of the studies described in this paper may stimulate such works.

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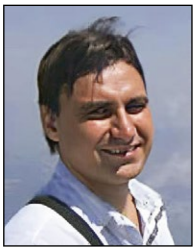
Alexander A. Tikhomirov,
Dr. of Biology Sciences, Professor. In 1970, he graduated from Krasnoyarsk State University by speciality in physics and qualification of biophysicist and physicist. At present, he works in the Biophysics Institute of the Siberian branch of Russian Academy of Sciences, head of the Phototroph Biosynthesis Control Laboratory, Head of the Closed Ecosystems sub-department of the Reshetnyov Siberian State University of Science and Technology. His research interests: phytoactinometry, light physiology of plants, closed ecosystems



Vladimir V. Velichko,
Ph. D. in Biology Sc. In 2003, he graduated from Krasnoyarsk State University by speciality in plant physiology and biochemistry. Currently, he works in the Biophysics Institute of the Siberian branch of the Russian Academy of Sciences as a senior researcher of the Phototroph Biosynthesis Control Laboratory. His research interests are photosynthesis and productivity of higher plants as phototrophic compartment of artificial ecosystems, effect of light conditions and mineral nutrition on growth and development of higher plants

Sofya A. Ushakova,
Ph. D. in Biology Sc. In 1968, she graduated from the Novosibirsk State University by speciality in physics and qualification of biophysicist and physicist. At present, she works in the Biophysics Institute of the Siberian branch of the Russian Academy of Sciences, leading researcher of the Phototroph Biosynthesis Control Laboratory. Her research interests: photosynthesis and productivity of higher plants as a component of artificial ecosystems, plant resistance against unfavourable ambient conditions